

OBTAINING COINCIDENT IMAGE OBSERVATIONS FOR
MISSION TO PLANET EARTH SCIENCE DATA RETURNLauri Kraft Newman*, David C. Folta**, and James P. Farrell^o

One objective of the Mission to Planet Earth program involves comparing data from various instruments on multiple spacecraft to obtain a total picture of the Earth's systems. To correlate image data from instruments on different spacecraft, these spacecraft must be able to image the same location on the Earth at approximately the same time. Depending on the orbits of the spacecraft involved, complicated operational details must be considered to obtain such observations.

If the spacecraft are in similar orbits, close formation flying or synchronization techniques may be used to assure coincident observations. If the orbits are dissimilar, the launch time of the second satellite may need to be restricted in order to align its orbit with that of the first satellite launched.

This paper examines strategies for obtaining coincident observations for Mission to Planet Earth spacecraft. Algorithms are developed which allow the estimation of the time between coincident observations for spacecraft in both similar and dissimilar orbits. Although these calculations may be performed easily for coplanar spacecraft, the non-coplanar case involves additional considerations which are incorporated into the algorithms presented herein.

INTRODUCTION

The Mission to Planet Earth (MTPE) program provides a constellation of satellites which will monitor the earth's processes from a variety of orbits by combining the resources of many individual instruments on different satellites. Data from one spacecraft can then be used in a specific scientific process with data from other spacecraft to either compare data taken over the same geolocation by different types of instruments, or to calibrate one instrument with another identical one on a different spacecraft. In order to acquire measurements which can be used in a complementary manner, the satellites must take measurements of the same geolocation at approximately the same time. Taking measurements of the same location with satellites in different orbits at the same time is a challenge which has several possible solutions. Placing two spacecraft which want to obtain coincident measurements in a formation flying configuration (as described in Reference 1) would allow these coincident measurements to be taken almost constantly over the mission lifetime. However, because each satellite has unique mission requirements and is a collection of instruments of different types, the orbits are usually dictated by science requirements, causing the orbits of two spacecraft instruments which are interested in obtaining coincident measurements to be dissimilar.

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This paper presents results of a study of obtaining coincident measurements between satellites in various orbits. Possibilities for selecting spacecraft orbits to maximize the occurrence of coincidences while meeting the science requirements of all spacecraft instruments are examined, using MTPE spacecraft as examples. Algorithms are developed and verified for the Shuttle Solar Backscatter Ultra-Violet (SSBUV) experiment which allow the estimation of the time between coincident observations for spacecraft in both similar and dissimilar orbits. Although these calculations may be performed easily for coplanar spacecraft using equations presented in Reference 2, the non-coplanar case involves additional considerations which are incorporated into the algorithms presented herein.

BACKGROUND

MTPE program scientists are interested in obtaining coincident measurements between instruments on multiple MTPE spacecraft. However, while some of these spacecraft are in very similar orbits, some are quite dissimilar. Table 1 lists some of the MTPE spacecraft and their mean orbital characteristics, developed through Flight Dynamics Division (FDD) analysis. The spacecraft are the EOS 10:30 a.m. mean local time (MLT) of descending node spacecraft (EOS-AM), the EOS 13:30 p.m. MLT of ascending node spacecraft (EOS-PM), the EOS Altimetry (EOS-ALT) spacecraft, and the Tropical Rainfall Measurement Mission (TRMM) spacecraft. In addition to the information provided in Table 1, all of these spacecraft are in frozen orbits, which implies that the spacecraft altitude over a given geolocation remains constant. The spacecraft which are in sun-synchronous orbits have a fixed right ascension of node with respect to the mean sun, which means that the nodal regression rate is defined to be 0.9856°/day. The polar orbit which is not sun-synchronous has a different regression rate, and its orbit plane is not fixed with respect to the mean sun. Figure 1 shows a three-dimensional view of these orbits.

Several possible combinations of these spacecraft orbits can be considered to determine the coincidences which occur between them. These possible orbit combinations are two sun-synchronous spacecraft, one sun-synchronous spacecraft and one polar (but not sun-synchronous) spacecraft, and one sun-synchronous spacecraft and one equatorial spacecraft. The combination of the sun-synchronous spacecraft with the polar (but not sun-synchronous) spacecraft is of value since the nodal regression rates of these two spacecraft are different, as described above. This means that the orbit planes are moving with respect to each other. The combination of the polar spacecraft with the equatorial spacecraft is not considered, since it is virtually identical to the sun-synchronous/equatorial case. The following sections examine the natural coincidences which occur between these orbit combinations. A coincidence, the time during which each of the two spacecraft see the same location, is defined herein to be 10 minutes. This timing is considered realistic, since the EOS-ALT scientists are interested in obtaining coincident measurements between instruments on EOS-ALT and those on EOS-AM and EOS-PM within 10 minutes. Another assumption made throughout this analysis is that the coincidences occur between nadir-looking instruments with 0° fields-of-view (FOV). Currently, the capability does not exist to consider finite instrument FOVs; however, this capability will be implemented in the near future. Finite FOVs would increase the duration and occurrence of coincidences as explained in Reference 3. Therefore, the analysis presented herein represents a worst-case scenario.

Table 1: MTPE Spacecraft Mean Orbital Characteristics

	EOS-AM	EOS-PM	EOS-ALT	TRMM
Semi-major Axis	7077.79 km	7077.59 km	7076.28 km	6729.39 km
Eccentricity	0.0012	0.0012	0.0013	0.00054
Inclination	98.205°	98.145°	94.0°	35.0°
Right Ascension	255.356°	273.17°	310.0°	0.0°
Epoch	6/30/98	12/01/02	06/01/02	10/01/97
Type of Orbit	Sun-Synchronous	Sun-Synchronous	Polar	Equatorial

APPROACH AND CONSIDERATIONS

In order to evaluate occurrences of coincident measurements, algorithms were developed by Ridge Technology which estimate the time between coincident observations. These algorithms are implemented in an adjunct utility of the Orbit Works software designed by Ridge Technology. Orbit Works is a PC-based analytical tool which uses a U.S. Space Command (USSC)/North American Air Defense (NORAD) Simplified General Perturbations (SGP4) analytical propagator to create ephemerides from two-line orbit elements. The drag term is set to zero, and station keeping orbit adjustments are not modeled. This yields what might be termed "ideal" low earth orbit (LEO) models, since the time of interest spans several years. Hence, the result must be viewed as representative rather than absolute. Therefore, a more accurate calculation of coincidence times can be accomplished by propagating the spacecraft orbits with a propagator in operational software such as the Goddard Mission Analysis System (GMAS), which includes the effects of orbital perturbations such as geopotential effects, third body perturbations, atmospheric drag, and solar radiation pressure. However, data processing from the long propagations obtained with GMAS involves examining each time step of the propagation to determine the exact time at which the latitudes and longitudes of the spacecraft are equal. This process is time consuming and tedious, and does not take into account the desired time between coincidences. Orbit Works takes advantage of knowledge of the implications of orbit geometry to reduce the computation of coincident measurements from an exhaustive search of the time window to a more limited search.

One strategy is to seed numerical searches about key events such as equator crossings. A second strategy is to note the periodicity of coincidences and use this knowledge to jump (in time) to the vicinity of the next possible event. This allows long runs to be made quickly which indicate graphically and in tabular form the coincident time periods for two spacecraft. Two versions of the software exist - one for two high inclination spacecraft, the other for one low and one high inclination spacecraft. These software packages both use the position vectors of the two spacecraft to find places where the orbits are aligned, signaled by a maximum in the dot product of the vectors, or a minimum of the cross product. However, the starting point for the searches is determined differently for each version, as explained in more detail in specific examples which follow.

While Orbit Works does not itself include the more complicated models such as those present in GMAS, coincidences over specific periods can be determined by fitting a least-squares approximation of a two-line element set to a solution produced by GMAS. The same method can be applied to fit an element set to an orbit determination solution after launch to refine estimates of imminent coincidences. This approach and methods are being used with success for determining coincident measurements between a space shuttle based instrument and several LEO spacecraft based instruments, as detailed below.

Validation of Orbit Works with SSBUV

Orbit Works has been tested in an operational environment for the SSBUV experiment, a Space Transportation System (STS) payload bay experiment to assess the calibration of the Solar Backscatter Ultra-Violet (SBUV/2) instruments on the odd numbered LEO National Oceanographic and Atmospheric Administration (NOAA) weather spacecraft. The NOAA spacecraft are in sun-synchronous orbit with a MLT of 13:30, an altitude of 850 km, an inclination of 99°, and an orbital period of approximately 100 minutes. The STS orbiter is launched into a 299 km nominal orbit inclined 28°, 34°, 39°, or 57° depending on mission payload requirements. Calibration transfer is derived from SSBUV common view of the same latitude and longitude as SBUV/2 within one hour (± 60 minutes) and at an 88° or less solar zenith angle. The requirement is to obtain at least 32 coincident measurements per spacecraft per mission. To date, six SSBUV missions have flown, with one more scheduled for 1994 (further flights are planned each year for the out years). The mission profiles are summarized in Table 2.

A critical pre-flight activity is assessing whether the SSBUV experiment objectives can be met for the nominal STS flight plan, taking into account the launch window variation. Mission planning for SSBUV

consists of simulating the nominal mission profile to determine if the SSBUV success criteria are satisfied. If conditions are marginal, the simulation is run for the entire range of launch date and times to determine the effect of launch time on the number of coincident measurements. A critical post-flight activity is to rapidly assess the data take, given the actual launch time and orbit. The Orbit Works mission design, planning, and operations tools, as well as SSBUV mission/instrument specific tools are used to perform these analyses.

Table 2: SSBUV Mission Characteristics

SSBUV	STS Mission	Launch Date	Inclination (°)
1	STS-34	18 Oct 89	34
2	STS-41	06 Oct 90	28
3	STS-43	02 Aug 91	28
4	STS-45	24 Mar 92	57
5	STS-56	08 Apr 93	57
6	STS-62	04 Mar 94	39
7	STS-66	27 Oct 94	57

The computation of coincidences is based on the observation that the SBUV/2 orbits are near polar, while the SSBUV orbit is near equatorial. Sunlit NOAA equator crossings are computed first, then the STS orbit is propagated forward and back in time to align it with the longitude of the NOAA equator crossing. The latitude range to be searched is restricted by the STS inclination while the longitude range is determined by the NOAA inclination.

The SSBUV experiment has provided a unique opportunity to compare the pre-flight predicted coincidences with those derived from post mission spacecraft navigation data and the SBUV/2 and SSBUV instrument data streams. Excellent temporal and spatial agreement was confirmed by checking SSBUV 1-3 coincidence data versus the Orbit Works predictions. For SSBUV-4, all coincidences were compared, and excellent agreement was found for common coincidences. There were some predicted coincidences that were not found in the data and vice-versa. These could be due to instruments mode, data dropout, deviations from the STS mission earth view timeline, data processing errors, etc. These differences were resolved with the SSBUV Experiment Office as part of a quality assurance program. A single discrepancy remains, which is attributable to the Orbit Works software finding a relative minima rather than an absolute minima, since multiple minima can occur during the large temporal constraint of ± 1 hour.

Once the SSBUV goal of 32 coincidences with SBUV/2 is met, mission objectives change to acquiring coincident measurements with other spacecraft instruments, such as the Nimbus-7 and Meteor 3-5 Total Ozone Mapping Spectrometer (TOMS) instruments, as well as with the Upper Atmosphere Research Satellite (UARS) Cryogenic Limb Array Etalon Spectrometer (CLAES) and Microwave Limb Sounder (MLS) (limb looking) instruments. Coincident measurements with ground based (Dobson) instruments at Boulder, CO and Mauna Loa, HI are routinely planned. In addition, Sulfur Dioxide (SO₂) observation opportunities over eastern continental US, Europe, and eastern Asia (China, Japan, Korea) are identified and integrated into the data collection plan.

Post mission estimates of actual data take is accomplished by using the actual earth view session times (times when the SSBUV instrument was actually operating) and two line elements sets fitted to navigation data contained in the Johnson Space Center (JSC) state vector summaries.

Methodology for MTPE Coincident Measurement Cases

The extensive testing that the Orbit Works Coincident Viewing utility has undergone with SSBUV lends confidence in extending these algorithms for use with MTPE satellites. The algorithms developed for use in analyzing coincidences between two polar MTPE spacecraft orbits are developed from but slightly different than those used for the equatorial SSBUV. Even though these algorithms cannot be fully

acceptance tested until flight data from two polar spacecraft is available, the SSBUV testing allows a measure of confidence in the analysis results. Three cases involving representative MTPE spacecraft were examined. These are classified by orbit inclination. Case 1 involves one sun-synchronous spacecraft and one equatorial spacecraft, Case 2 considers one sun-synchronous spacecraft and one polar (but not sun-synchronous) spacecraft, and Case 3 includes two sun-synchronous spacecraft. Initially, Case 2 was thought to be included in the methods for Case 3; however, the converse proved to be true. That is, the methods developed to evaluate Case 2 also permit evaluation of Case 3. For all cases, a temporal constraint of observation within ten minutes was applied.

Case 1 (Sun-synchronous versus Equatorial)

The first coincident viewing case examined is the comparison between a high inclination, sun-synchronous spacecraft (EOS-AM) and a low inclination, equatorial spacecraft (TRMM). The methodology used in examining the coincidences which occur for this case is the same as that used for SSBUV, without some SSBUV mission specific extensions. For case 1, all equator crossings are checked, no sun angle constraint is applied, and the temporal constraint is 10 minutes.

The time and longitude of the ascending and descending equator crossings for the high inclination spacecraft are computed. The low inclination spacecraft position at the equator crossing time is then moved clockwise and counter-clockwise to the longitude of the high inclination crossing event. The time range to search, dt_1 , is defined by the time required for the polar spacecraft to transit the possible latitude range of the low inclination spacecraft. This is approximated from spherical trigonometry by:

$$dlat = \sin^{-1} \left(\frac{\sin i_2}{\sin i_1} \right)$$

$$dt_1 = \frac{dlat}{n_1}$$

where n denotes mean motion in radians per day, i denotes inclination, and $dlat$ denotes change in latitude in radians. Subscript 1 refers to the low inclination spacecraft (TRMM), and subscript 2 refers to the high inclination spacecraft (EOS-AM). Mean motion is calculated as:

$$n = \sqrt{\frac{\mu}{a^3}}$$

where μ is the earth's gravitational constant and a is the orbit semi-major axis.

The search range for the low inclination spacecraft is defined by the time, dt_2 , required for the low spacecraft to transit the same longitude range as the high spacecraft, in crossing the latitude range of the low spacecraft. This is estimated by:

$$dlon = \sin^{-1} \left(-\frac{\tan i_2}{\tan i_1} \right)$$

$$dt_2 = \frac{dlon}{n_2}$$

where $dlon$ denotes change in longitude in radians.

These times can be used to form a box over which a search can be performed for a position vector dot product maxima. The limits of the box, as shown in Figure 2, are from $t_1 - dt_1 - t_c$ to $t_1 + dt_1 + t_c$ on one axis

and from $t_2-dt_2-t_c$ to $t_2+dt_2+t_c$ on the perpendicular axis, where t_c is the time constraint of 10 minutes assumed for this analysis. An iterative search is then conducted to find a minima of the position vector cross product within this box. The box is divided into a grid of 625 equal sections. The section containing the minima is then further subdivided onto 625 equal sections, and so forth until the time intervals are both below a constraint (assumed to be one second). This refinement isolates the location of the minima. The one second criteria is justifiable, since the spacecraft position knowledge would be less than one second. This process is then repeated for the next node crossing to determine the next coincidence.

Case 2 (Sun-synchronous versus Polar)

This case involves two spacecraft: EOS-AM, a high inclination, sun synchronous spacecraft and EOS-ALT, a high inclination, polar spacecraft. The difference in the respective nodal regression rates means that the right ascension of the ascending nodes will cross about every two years, with a crossing while the spacecraft are traveling in opposite directions once per year. The method used for case 1 of determining a longitude box to seed the search for a cross-product minima could not be extended to cover this case, and the prediction of coincident measurement opportunities for this case proved to be somewhat challenging.

To investigate the nature and frequency of the coincidences, the behavior of the dot product of the position vectors of the two spacecraft was examined. This led to a methodology which entailed detection of the maximum extremae of the dot product or detection of the upper envelope of that function. Both orbits are propagated in steps of one minute using the analytic propagator, and the dot product of the geocentric inertial (GCI) position vectors is computed at each step. Figure 3 shows the value of the extrema over a five year period.

The time of the value of each maxima is then used to seed a search for a geocentric fixed (GCF) nadir trace crossing. The search is performed by bracketing the time of the maxima of the dot product by \pm the temporal constraint and performing a two-dimensional search for a minima of the cross product of the GCF position vectors. Figures 4 through 8 show the temporal and spatial distribution of the coincidences. The map shows the spatial distribution, while the timeline on the bottom of the figure shows when these coincidences occur during the year. Note that each figure contains a one year portion of the five year span shown in Figure 3, and that the temporal distribution of coincidences in each figure corresponds directly to the dot product maxima shown in Figure 3.

Case 3 (Sun-synchronous versus Sun-synchronous)

This case is a variant of case 2, with both spacecraft (EOS-AM and EOS-PM) in high inclination, sun-synchronous orbits. Since by definition the relative right ascension is constant (i.e. $\Omega_1 - \Omega_2 = C$), this case reduces to determining the longitude of crossings when they occur within the temporal constraint. The latitude of the coincidences can be computed from the orbit geometry - where the orbit planes cross - one in the northern hemisphere and one in the southern hemisphere. Passage of one spacecraft through the computed latitude can be used to seed a search for coincident observation by the second spacecraft. Since these passages are periodic, the searches are confined to the temporal constraint period of time twice a revolution. In practice, the methods developed for case 2 accommodated this case (but not necessarily vice-versa). For extensive application, an implementation capitalizing on the large (1/2 rev) jump between searches would economize computation time. The dot product extrema are shown in Figure 9.

RESULTS

This section discusses results of analyses of the three cases discussed above. The identified coincident measurement opportunities for each case are characterized by temporal characteristics, spatial characteristics, quantity of coincidences, and quality of coincidences (e.g. lighting conditions).

Case 1 (Sun-synchronous versus Equatorial)

Figure 10 shows a typical year of EOS-AM and TRMM coincidences. This represents several coincidences occurring daily on consecutive revs. On the average, half of these coincidences are sunlit. Note that in this case, the equatorial spacecraft was also at a much lower altitude than the sun-synchronous spacecraft. Figure 11 shows the relationship between the lighting conditions and the latitude at the coincidence location for a short (6 day) period during the year. Opportunities for coincidences in this case are characterized by a temporal characteristic of about 5 coincidences each day on consecutive revs, and a spatial characteristic of a full range of latitude and longitude locations within the orbit inclination constraints. The quantity of coincidences is about 2,200 coincidences per year for the EOS-AM and TRMM orbits, with a quality of 50% sunlit (the latitude varies with relative right ascension of node).

In fact, the availability of coincident measurement opportunities is dominated by the difference in mean motion of the EOS-AM and TRMM orbits of over one revolution (rev) per day. Coincident measurement opportunity analyses for other spacecraft which can be characterized as low inclination, low altitude, low eccentricity can be accommodated by this case. The algorithm must be further tested to determine its ability to handle low inclination spacecraft orbits which are high in either altitude or eccentricity.

Case 2 (Sun-synchronous versus Polar)

For the EOS-AM and EOS-ALT case, the results were somewhat surprising. The temporal pattern of coincidences is aperiodic in the five year interval we examined. Figure 5 shows a period of coincidences over seven (7) weeks which samples a wide range of earth locations. Figure 12 shows how this corresponds to a time when both the difference in right ascension of the ascending node and mean anomaly were near zero. Figure 13 shows the same information for the coincidences in Figure 7. Note that the availability of sunlit coincidences depends largely on the sun declination. Opportunities for coincidences in this case are characterized by a temporal characteristic of biannually for a period of either approximately 30 or 45 days, and a spatial characteristic which varies based on relative right ascension and mean anomaly. Opportunity exists for a period of observations which cover a full range (latitude and longitude) of geolocations at the times when the orbit planes intersect. The quantity of coincidences is approximately 600 to 1400 per year, with a quality of 50 % sunlit either all North or South latitude, except during right ascension of node crossover.

Polar or sun-synchronous spacecraft which fall into this category may be synchronized in mean anomaly or right ascension (if mission requirements are not violated) to maximize the number of coincidences. For instance, the right ascension of EOS-ALT was not specified by the science requirements. Therefore, some freedom in choosing this variable to maximize the coincidences with EOS-AM over the EOS-ALT lifetime is allowed. Figure 14 shows the coincidences between EOS-AM and EOS-ALT for a five year period, assuming that the EOS-ALT right ascension is chosen to be 310° . This choice was made by FDD to ensure that the first coincidence would occur after the initial EOS-ALT checkout period was complete (Reference 4). The fact that the spacecraft are traveling in the same direction the first year and opposite directions the second is clearly indicated by the long coincidences in the odd years (1, 3,...) followed by the multiple, short coincidences in the even years (2, 4,...). The lack of periodicity of the coincidences is also clearly evident.

Case 3 (Sun-synchronous versus Sun-synchronous)

For this case, the difference in spacecraft orbital periods results in a period of coincidences which occurs approximately once every 5 years for a period of about 12 months. Figures 15 and 16 show the spatial and temporal distribution of these coincidences. As expected, the coincidence location latitude is approximately 69.5° North and South of the equator. Figure 17 demonstrates that the variation of sun lighting conditions at the coincidence location depends solely on the sun declination. Opportunities for

coincidences in this case are characterized by a temporal characteristic of one twelve month period of coincidences during a five year mission, and a spatial characteristic which is confined to a single latitude North and South of the equator. The quantity of coincidences is approximately 11,000 coincidences, with a quality of 50% sunlit either North or South latitude, which reverses with annual variation of sun declination.

Again, polar or sun-synchronous spacecraft which are representative of this category may be synchronized in mean anomaly or right ascension (if mission requirements are not violated) to maximize the number of coincidences.

CONCLUSION

If coincident viewing requirements are levied on MTPE spacecraft orbits, numerical analysis must be performed to determine the coincidence times, since the co-planar coincidence algorithms presented in Reference 2 cannot be extended to cover the non-coplanar case. As evidenced by the above analysis, the PC-based Orbit Works tool provides a quick, easy, and economical way to numerically determine the coincident viewing periods for any two given spacecraft. Since spacecraft orbits are usually determined based on mission requirements, Orbit Works can be used to show the coincidence times which occur naturally between two given spacecraft orbits within a given temporal constraint. If the naturally occurring coincidences are inadequate, several options are available to ameliorate the situation. First, the launch of a second satellite can be planned to maximize coincidences with a satellite already on-orbit by varying the launch date and/or right ascension of the node of the second spacecraft. Secondly, the position of the second spacecraft in its orbit can be aligned with the position of the first such that each spacecraft passes through perigee at the same time. Finally, if the spacecraft are in similar orbits, close formation flying or synchronization techniques may be used to assure coincident observations. Orbit Works can be used to incorporate these coincident viewing considerations into future mission orbit selection, launch window analysis, operations and science planning for on-orbit spacecraft, or instrument calibration on multiple spacecraft.

The analysis presented herein assumes that both spacecraft orbits are fixed, and that the naturally occurring coincident periods (within the temporal tolerance) are sufficient to meet mission coincident viewing goals. No attempt was made to alter the mission orbits to maximize coincidences (with the exception of the EOS-ALT right ascension), as the orbits for MTPE spacecraft are specified by science requirements. It is also possible with Orbit Works to use the first spacecraft and a given temporal constraint to choose the orbit for the second spacecraft such that the number of coincidences is maximized. Choosing the second orbit to maximize coincidences is dependent on the ability of that orbit to meet the other mission science requirements.

REFERENCES

1. Folta, David, et al., "Considerations on Formation Flying Separations for Earth Observing Satellite Missions", AAS/AIAA Spaceflight Mechanics Meeting, Colorado Springs, CO, Feb. 24-26, 1992.
2. "Rendezvous/Proximity Operations Workbook", NASA JSC, Feb. 1985.
3. Scolese, Christopher, et al., "Field of View Location and Formation Flying for Polar Orbiting Missions", AAS/AIAA Spaceflight Mechanics Meeting, Houston, TX, Feb. 11-13, 1991.
4. "EOS-ALT Phase A Final Report Input," L. Newman to G. Smith, dtd. 12/23/93.

BIBLIOGRAPHY

Methods of Orbit Determination; P.R. Escobal; Krieger Publishing Company; 1976

Models for Propagation of NORAD Element Sets, Spacetrack Report No. 3; Felix R. Hoots & Ronald L. Rochrich; December 1980 (NTIS accession number: ADA 093554; Phone (703) 487-4650)

Orbit Works Reference Manual, Version 5.0, Ridge Technology, March 1994

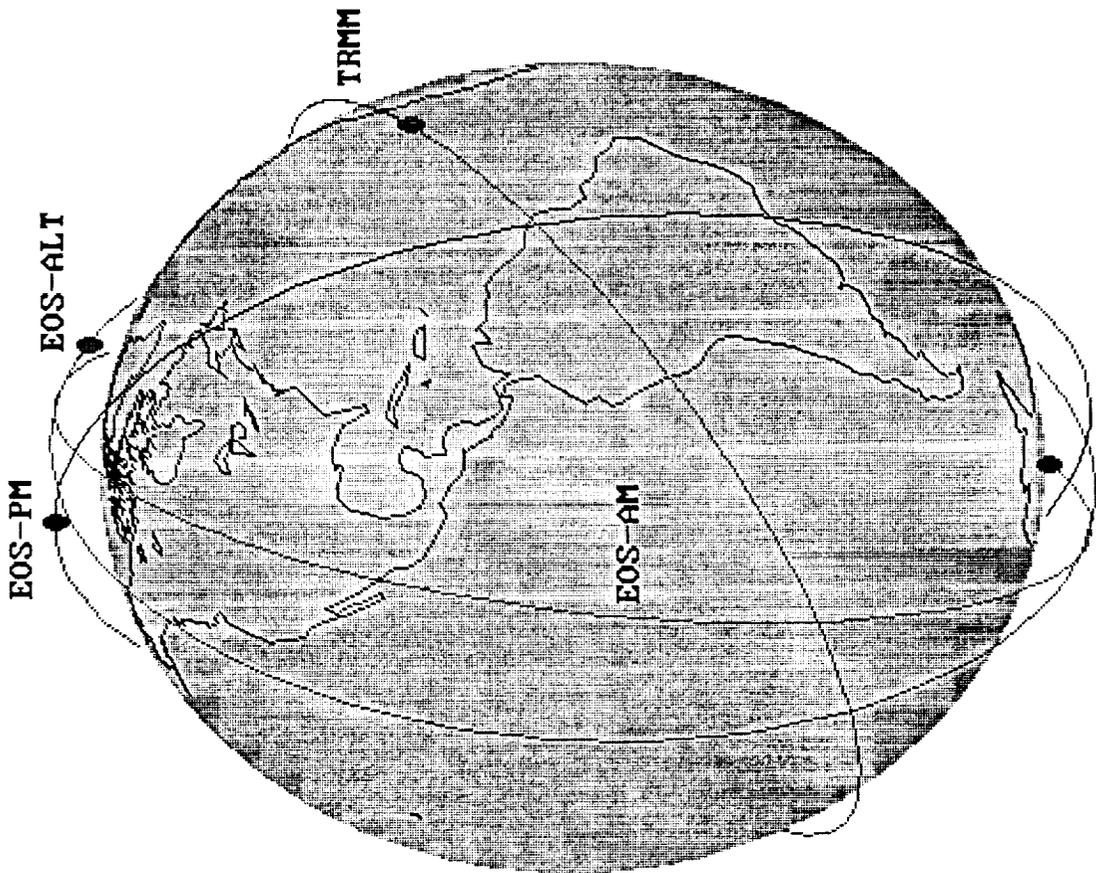


Figure 1: MTPE Spacecraft Orbits

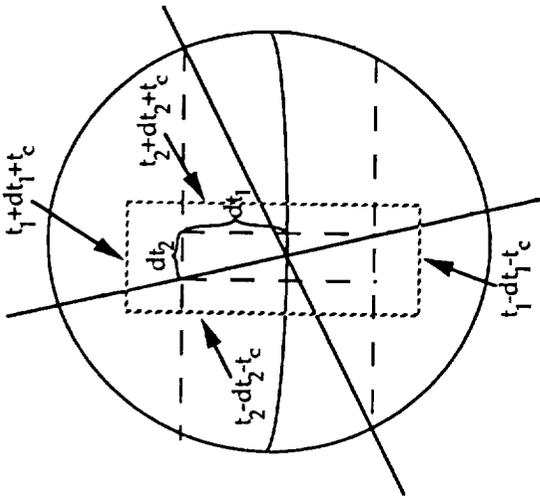


Figure 2: Case 1 Search Box

Instrument Track Coincident Earth Views
 Problem Set: c4318-07 System: CD318
 Date/time: Start: 81JAN2887 8888888 Stop: 81JAN2888 8888888
 Coincident measurement for alt boi w/range=310 (2887)

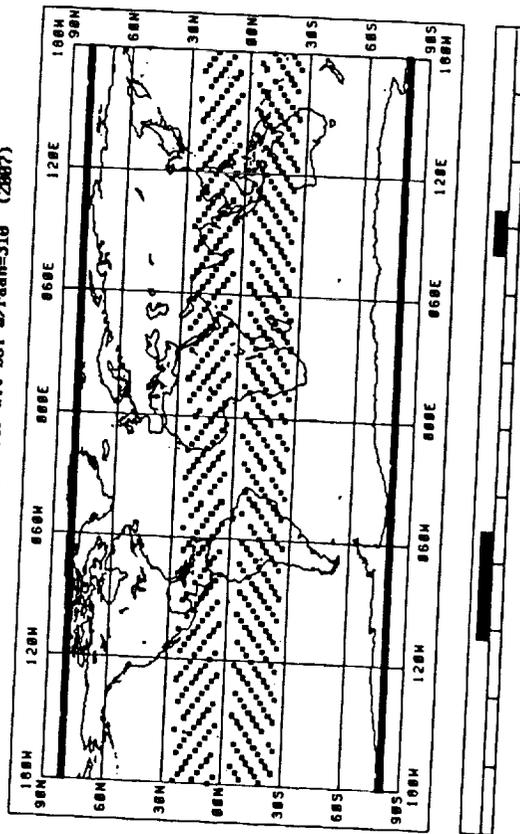


Figure 4: Case 2 Coincidences During 2007

Position Vector Dot Product
 Problem Set: CD318 System: CD318
 Date/time: Start: 81JAN2887 8888888 Stop: 81JAN2812 8888888
 Coincident measurement for alt boi w/range=318

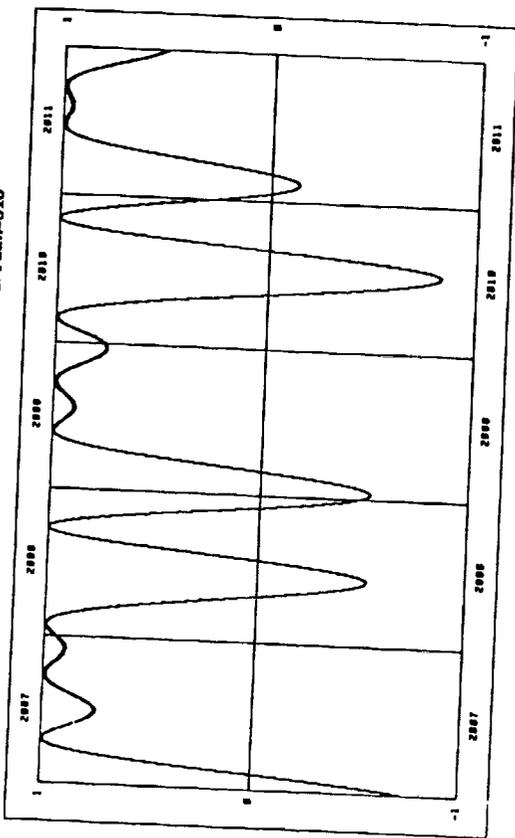


Figure 3: Position Vector Dot Products for EOS-AM and EOS-ALT

Instrument Track Coincident Earth Views
 Problem Set: c4318-08 System: CD318
 Date/time: Start: 81JAN2888 8888888 Stop: 81JAN2889 8888888
 Coincident measurement for alt boi w/range=310 (2888)

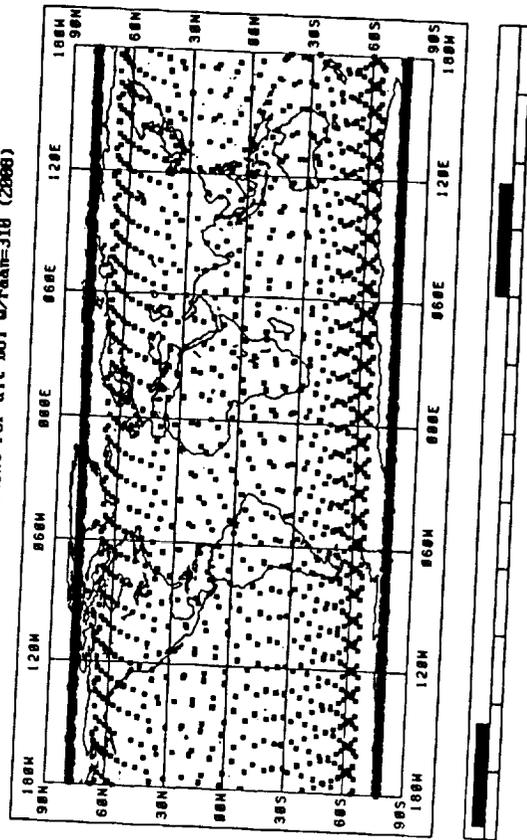


Figure 5: Case 2 Coincidences During 2008

Instrument Track Coincident Earth Views
 Problem Set: cd318-10 System: CD318
 Problem Set: 81JAN2810 868888 Stop: 81JAN2811 868888
 Date/time: Start: 81JAN2810 060000 Stop: 81JAN2810 060000
 Coincident measurement for alt bol w/raam=318 (2810)

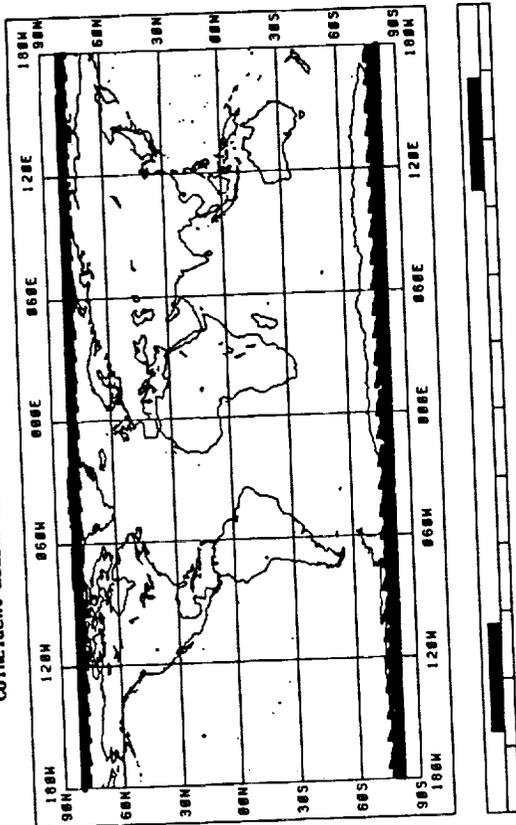


Figure 7: Case 2 Coincidences During 2010

Position Vector Dot Product
 Problem Set: AMR2 System: AMR2
 Problem Set: 81JAN2862 868888 Stop: 81JAN2867 868888
 Date/time: Start: 81JAN2862 060000 Stop: 81JAN2867 060000
 Coincident measurement for PM w/AM

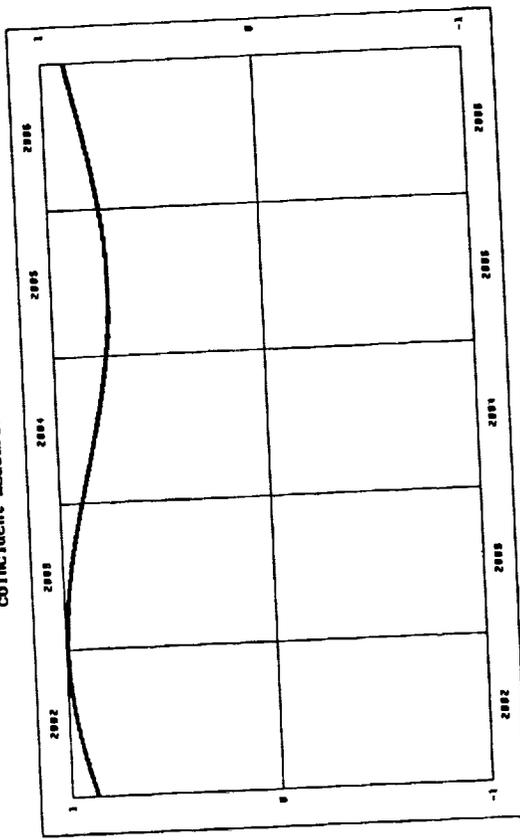


Figure 9: Position Vector Dot Products for EOS-AM and EOS-PM

Instrument Track Coincident Earth Views
 Problem Set: cd318-09 System: CD318
 Problem Set: 81JAN2809 868888 Stop: 81JAN2810 868888
 Date/time: Start: 81JAN2809 060000 Stop: 81JAN2810 060000
 Coincident measurement for alt bol w/raam=318 (2809)

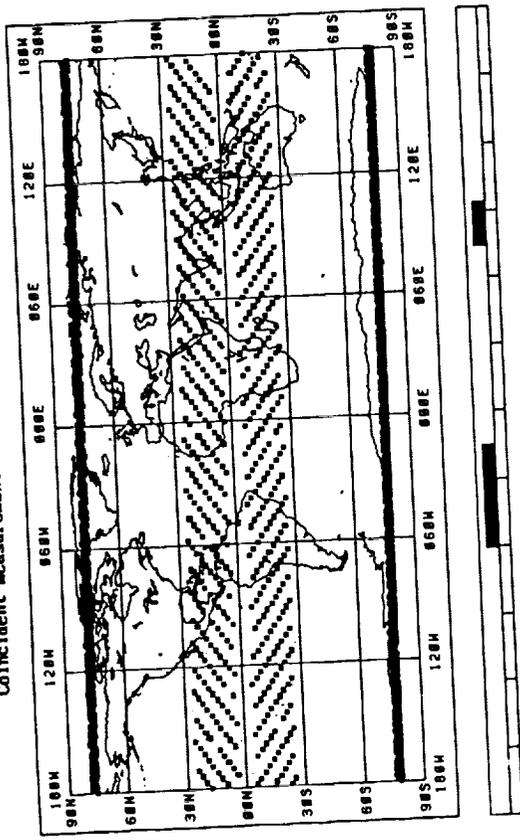


Figure 6: Case 2 Coincidences During 2009

Instrument Track Coincident Earth Views
 Problem Set: cd318-11 System: CD318
 Problem Set: 81JAN2811 868888 Stop: 81JAN2812 868888
 Date/time: Start: 81JAN2811 060000 Stop: 81JAN2812 060000
 Coincident measurement for alt bol w/raam=318 (2811)

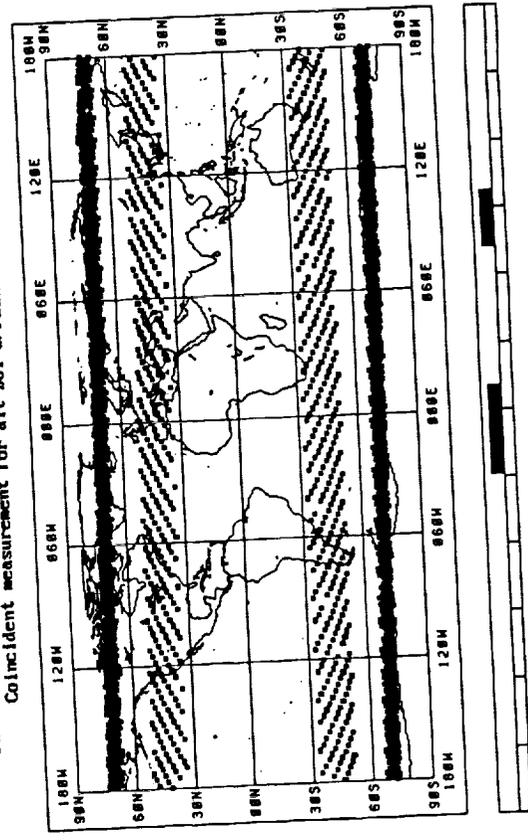


Figure 8: Case 2 Coincidences During 2011

Instrument Track Coincident Earth Views
 Problem Set: amtraw System: AMTRAW
 Date/Time: Start: 81JAN1998 888888 Stop: 81JAN1999 888888
 coincident measurement for TRM with AT

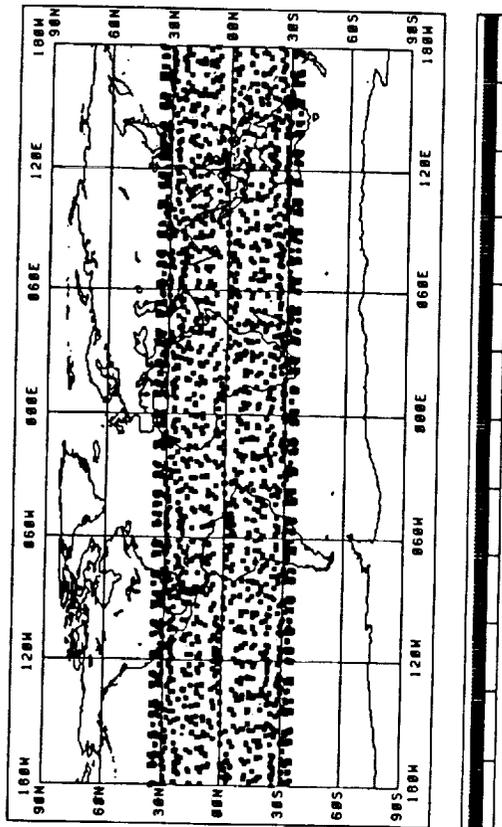


Figure 10: Case 1 Coincidences During 1998

Nadir Local Solar Time vs. Latitude
 Date: 81OCT2888 for 6 days Every 1.8 days System: CD310
 Sun right ascension: 187.51 Declination: -3.24

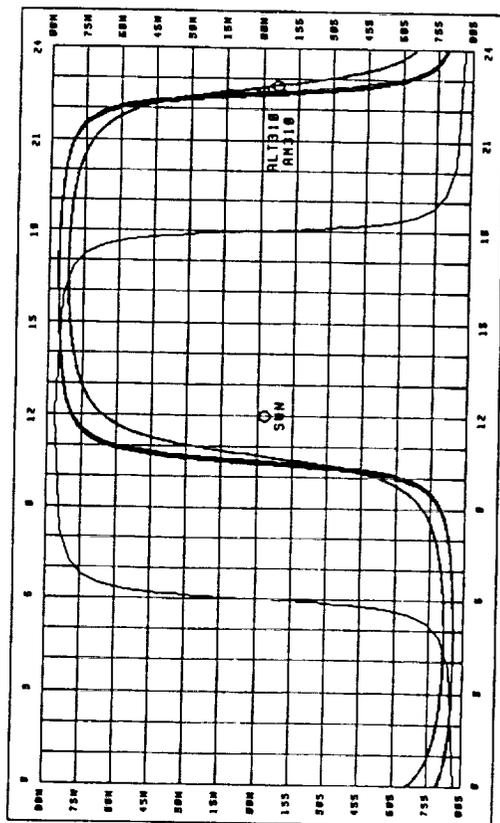


Figure 12: Nadir Local Solar Time Versus Latitude During 2008 (Case 2)

Nadir Local Solar Time vs. Latitude
 Date: 81JAN1998 for 6 days Every 1.8 days System: AMTRAW
 Sun right ascension: 281.26 Declination: -23.84

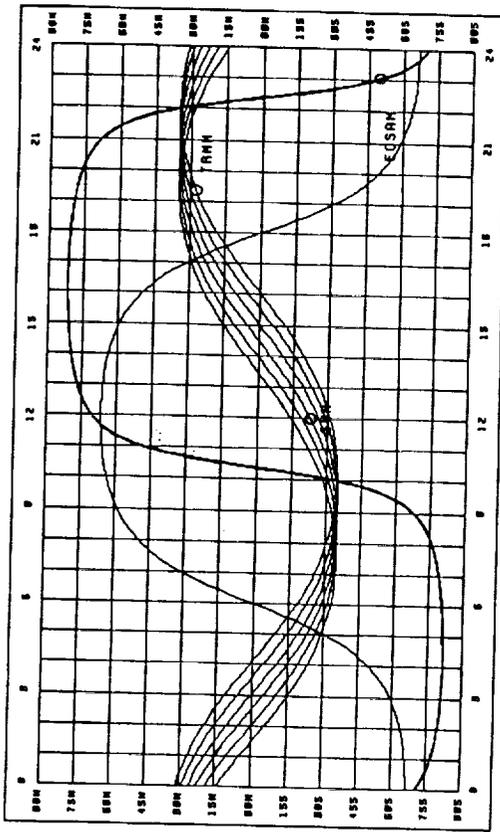


Figure 11: Nadir Local Solar Time Versus Latitude (Case 1)

Nadir Local Solar Time vs. Latitude
 Date: 81MAR2810 for 6 days Every 1.8 days System: CD310
 Sun right ascension: 341.88 Declination: -7.71

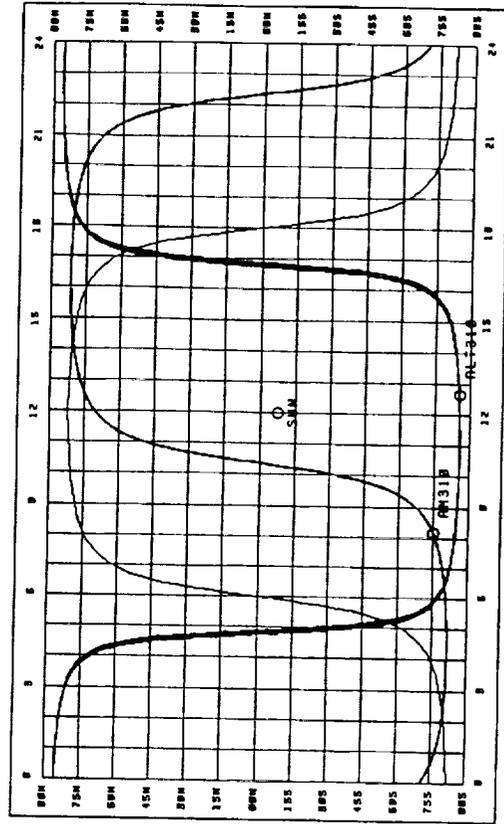


Figure 13: Nadir Local Solar Time Versus Latitude During 2010 (Case 2)

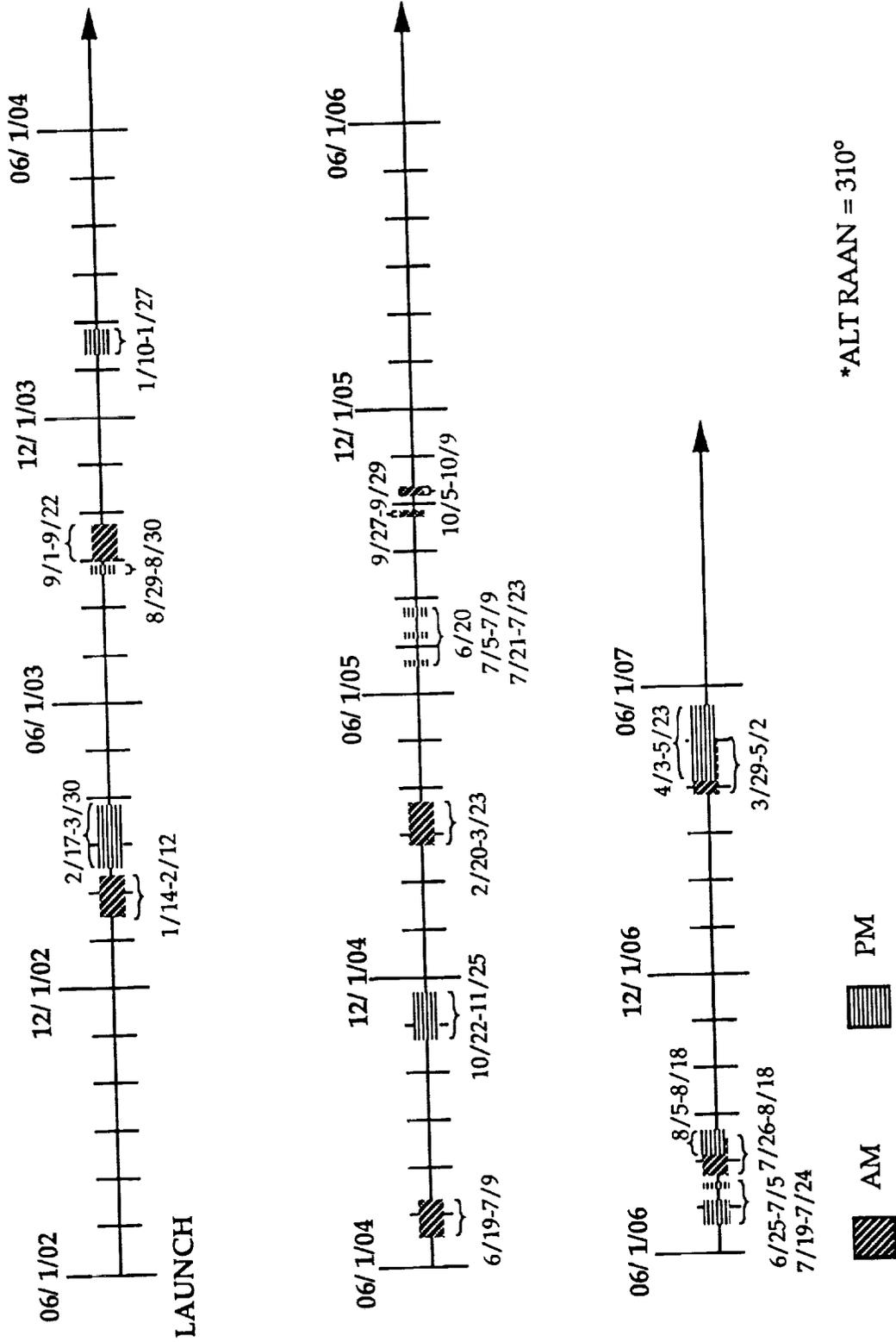


Figure 14: EOS-ALT Coincidences with EOS-AM and EOS-PM

Instrument Track Coincident Earth Views
 Problem Set: amp-82 System: AMPZ
 Date/Time: Start: 81JAN2882 888888 Stop: 81JAN2883 888888
 Coincident measurement for PM w/AM (2882)

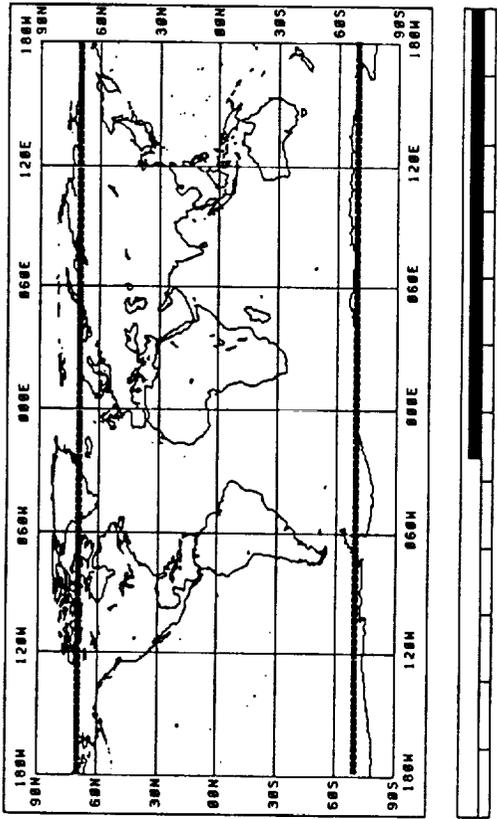


Figure 15: Case 3 Coincidences During 2002

Instrument Track Coincident Earth Views
 Problem Set: amp-83 System: AMPZ
 Date/Time: Start: 81JAN2883 888888 Stop: 81JAN2884 888888
 Coincident measurement for PM w/AM (2883)

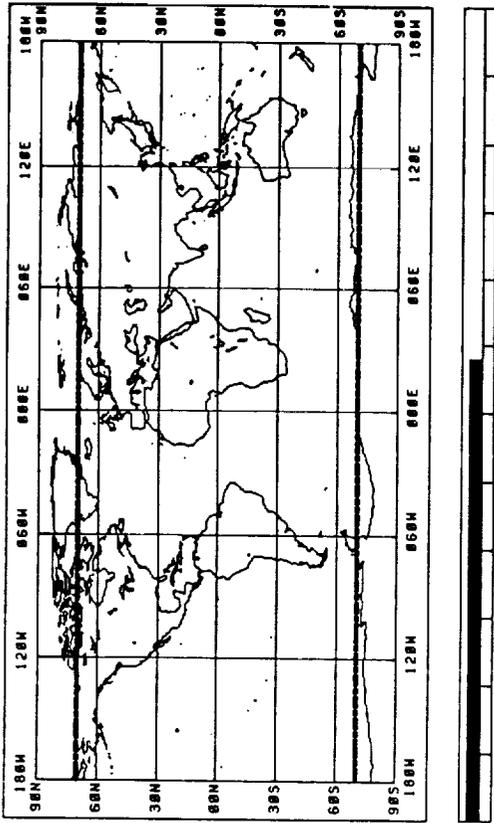


Figure 16: Case 3 Coincidences During 2003

Nadir Local Solar Time vs. Latitude
 Date: 81JAN2883 for 6 days Every 1.8 days System: AMPZ
 Sun right ascension: 281.83 Declination: -23.85

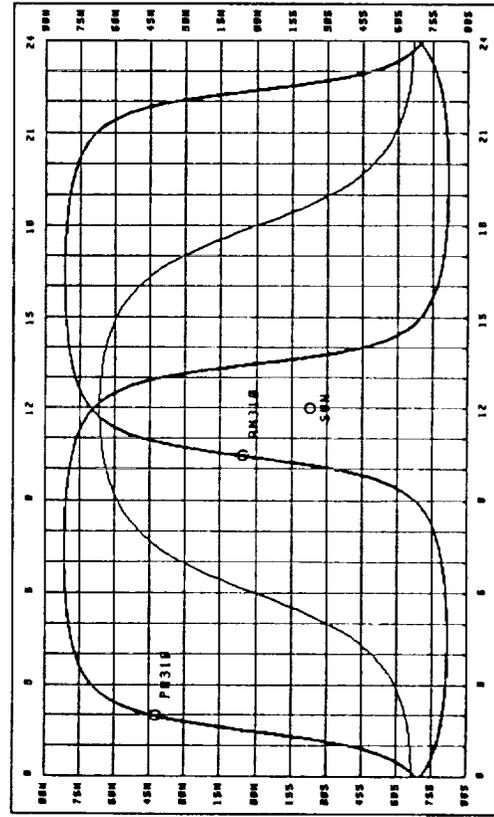


Figure 17: Nadir Local Solar Time Versus Latitude (Case 3)

